WHITE PAPER

Improve Measurement Integrity

RF and microwave wideband signal generation

KEYSIGHT

Introduction

The wireless communication industry is experiencing massive technology advances across multiple systems. Cellular communication is transitioning from 4G to 5G to enable extreme data throughputs, and satellite communication providers are building networks in space to enable high-speed communications from anywhere. Wi-Fi stakeholders use the 6 GHz band to increase peak throughput via 1.2 GHz of accessible and unlicensed spectrum. What is the one thing these developments have in common? They all demand higher frequency bands and wider channel bandwidths to achieve the required data throughput.

Engineers must develop an accurate and reliable test system that delivers optimal performance to meet the requirements of these technology developments. Calibrating wideband channels at RF, microwave, and millimeter-wave frequencies presents challenges. This white paper covers the impact of frequency responses and modulator imperfections on wide bandwidth signals and how you can improve measurement integrity.

Wide Bandwidth Applications

Exponential growth for faster data rate applications has triggered the need for new technologies capable of wide signal bandwidth. A variety of spectrum allocations at higher frequencies support wider bandwidths that provide a faster data rate. Meanwhile, regulators have addressed the need for an additional spectrum with new standards.

Satellite and non-terrestrial networks

Satellite communications provide connectivity for television, phone, broadband internet services, and military communications. Satellites operate in a large number of frequency bands; the use of each band was determined by international regulations and applications, as shown in Table 1. As the C and Ku bands grow increasingly congested, global interest in the Ka-band for commercial satellite communications has risen sharply. The International Telecommunication Union (ITU) allocates the 71–76 GHz / 81–86 GHz segment of the W band to satellite services. These frequency segments are of increasing interest to commercial satellite operators for wider bandwidths. Increasing channel bandwidth enables higher data rates per client and extends the number of channels for higher system capacity. High-throughput satellites now use transponders with bandwidths up to 500 MHz to achieve required data rates.

Table 1. Satellite frequency usages and applications

Frequency band	Frequency range (GHz)	Allocation for satellite (GHz)	Major applications
L	1 to 2	1.5 to 1.7	Mobile satellite services
			Navigation systems
S	2 to 4	2.0 to 2.7	Mobile satellite services
			Digital audio radio services
C	4 to 8	3.7 to 4.2 (DL)	Fixed-satellite TV, data, and broadcasting services
		5.9 to 6.4 (UL)	
		7.3 to 7.8	Military communications
X	8 to 12	7.25 to 8.4	Military communications
Ku	12 to 18	10.7 to 13.25	Fixed-satellite TV, data, and broadcasting services
		14.0 to 14.5	
K	18 to 26.5	17.3 to 21.2	Wide bandwidth communications
Ka	26.5 to 40	27.5 to 40.0	Fixed-satellite TV, data, two-way broadband services
			Mobile-satellite, inter-satellite
			Military communications

Since 2018, the telecommunication industry has been developing standardization studies on the benefits of satellite coverage as part of the mix of access technologies for 5G. The Third Generation Partnership Project (3GPP) Release 14 investigated satellite deployment scenarios. Release 15 defined the network architecture, and Release 16 has identified use cases to provide services with satellite integration in the 5G Radio Access Network (RAN). Satellite communications are an essential part of the 5G infrastructure. The channel bandwidth of the 5G NR non-terrestrial network (NTN) goes up to 800 MHz at K-band (downlink) and Ka-band (uplink) for satellite communications. The bandwidth can go up to 1,800 MHz for unmanned aerial systems (UAS).

5G new radio

Enhanced Mobile Broadband (eMBB) is one of use cases defined for 5G New Radio (NR). It uses new and existing technologies to achieve the anticipated extreme data throughputs, including wider channel bandwidths, carrier aggregation, high modulation density, and multiple antennas. The 5G NR maximum channel bandwidth is 400 MHz for the frequency range 2 (FR2), and the maximum aggregated channel bandwidth (intra-band contiguous) goes up to 1.2 GHz. Table 2 represents the maximum channel and aggregated bandwidths for the evolving 3GPP standards.

Table 2. The bandwidth of the 3GPP wireless standards

Standard	Revision	Maximum channel bandwidth	Maximum aggregated channel bandwidth (intra-band contiguous)
3GPP 4G	LTE (R8)	20 MHz	NA
	LTE-A (R10)	20 MHz	100 MHz
	LTE-A Pro (R13-14)	20 MHz	640 MHz
3GPP 5G [1]	NR (R15) FR1	100 MHz	400 MHz
	NR (R15) FR2	400 MHz	1200 MHz

1. 3GPP TS 38.101-1/2 V16.0.0 UE conformance specification, radio transmission, and reception

Wireless LAN

The Institute of Electrical Electronics Engineers (IEEE) and Wi-Fi Alliance developed the 802.11 standard, an evolving family of specifications for wireless local area networks (WLAN). The requirements of wireless data services continue to increase in many scenarios — the Wi-Fi community's target is at the maximum throughput of up to 30 Gbps. With the new 6 GHz frequency band, the IEEE 802.11be task group introduces channels as wide as 320 MHz. The wider bandwidth can double the maximal nominal throughput for the existing 802.11ax standard. Table 3 illustrates the frequency bands and maximum channel bandwidths for IEEE 802.11 standards.

Table 3. IEEE 802.11 wireless standards bandwidths

IEEE	Public name	Frequency band	Maximum bandwidth	Modulation/ sub-carrier
802.11n	Wi-Fi 4	2.4 GHz	40 MHz	OFDM / 64 QAM
802.11ac	Wi-Fi 5	2.4 and 5 GHz	80 MHz	OFDM / 64 QAM
802.11ax	Wi-Fi 6	2.4, 5, and 6 GHz	160 MHz	OFDM / 1,024 QAM
802.11be [1]	EHT [2]	2.4, 5, and 6 GHz	320 MHz	OFDM / 1,024 QAM
802.11ad	WiGig	60 GHz	2.16 GHz	OFDM / 64 QAM
802.11ay	n/a	60 GHz	2.16*2 GHz	OFDM / 64 QAM

1. Targeted completion in 2023
2. Extremely high throughput

Wide Bandwidth Signal Generation

While increasing signal bandwidth offers a great way to achieve faster data rates, it introduces a new challenge to meet the signal quality requirements at higher frequency ranges. For example, channel flatness typically decreases as channel bandwidth increases. In addition, wideband I/Q modulator imperfection results in poor modulation quality. Testing these wide bandwidth designs requires the use of advanced measurement technologies.

The following are three common solutions to generate wide bandwidth signals at high frequencies:

- Use an arbitrary waveform generator (AWG) to generate baseband I and Q signals; upconvert the signals to the desired frequency with a vector signal generator (VSG).
- Generate an intermediate frequency (IF) signal with a wideband VSG and upconvert the IF signal to the desired frequency by a frequency extender.
- Produce the signals required with a fully integrated, calibrated wideband VSG.

Table 4 displays the three different solutions for wide bandwidth signal generation. The first two solutions integrate multiple instruments to generate the desired wideband signals. These test setups require to perform system calibrations to minimize the frequency channel responses across the entire bandwidth. In addition to flattening the channel frequency responses of the system, the calibrations also eliminate I/Q modulator imperfections. The fully calibrated VSG, such as M9484C and M9384B, provides < ± 0.9 dB RF amplitude flatness across the entire modulated bandwidth with factory channel corrections.

Table 4. Solutions for wide bandwidth vector signal generation

	BBIQ + VSG	IF + upconverter	Fully calibrated VSG	
				
Example	M8190A and E8267D	S9130A	M9384B or M9383B	M9484C
Frequency	Up to 44 GHz	< 6 GHz 24.25 to 43.5 GHz	Up to 44 GHz	Up to 54 GHz (110 GHz[1])
Max. bandwidth	2 GHz	1.2 GHz	2 GHz (4 GHz)	2.5 GHz (5 GHz[2])
System calibration	Required	Required	Calibrated	Calibrated
Output power (CW) at 40 GHz	+19 dBm	+10 dBm	+19 dBm	+ 24 dBm
Modulation quality	Excellent	Good	Excellent	Excellent
Number of channel	1	Up to 8	Up to 2	Up to 4

1 Use Keysight V3080A frequency extender to extend the frequency range

2 Use channel bonding technique

Frequency response

When a signal generator outputs a modulated signal, the components inside the signal generator — such as mixers, filters, and amplifiers — contribute frequency responses. The responses in the amplitude and phase of the modulated signal degrade modulation quality. These responses occur at different frequencies and output levels and include amplitude and phase responses.

Figure 1 illustrates a 64 QAM demodulation analysis at a 100 MHz symbol rate. The I/Q constellation (upper left) is chaotic due to the wide bandwidth frequency responses, so the signal cannot demodulate correctly.

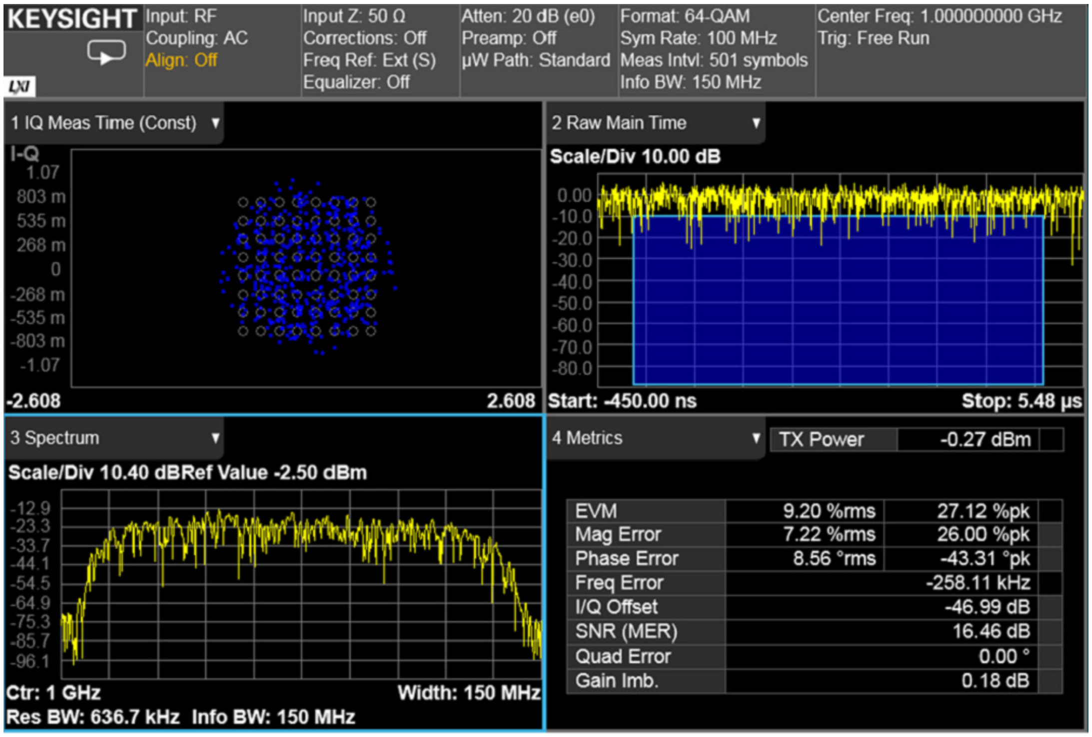

Figure 1. Frequency response impacts on signal modulation quality

When you enable adaptive equalization on the signal analyzer, you can observe the signal's amplitude response (upper right) and phase response (lower right), as shown in Figure 2. The deviation of the amplitude response across the analysis bandwidth (156.3 MHz) is 0.8 dB, and the deviation of phase response is 0.3 degrees. After removing the frequency responses with an equalization filter, the I/Q constellation (upper left) is clear, and the error vector magnitude (EVM) stands at 0.19%. To improve measurement integrity for wideband signal generation, you need to apply a correction filter to a signal generator to minimize the effects of frequency responses.

What is adaptive equalization?

Adaptive equalization removes linear errors from modulated signals by dynamically creating and applying a finite impulse response (FIR) compensating filter.

The errors include group-delay distortion, frequency-response errors, and reflections, or multipath distortion.

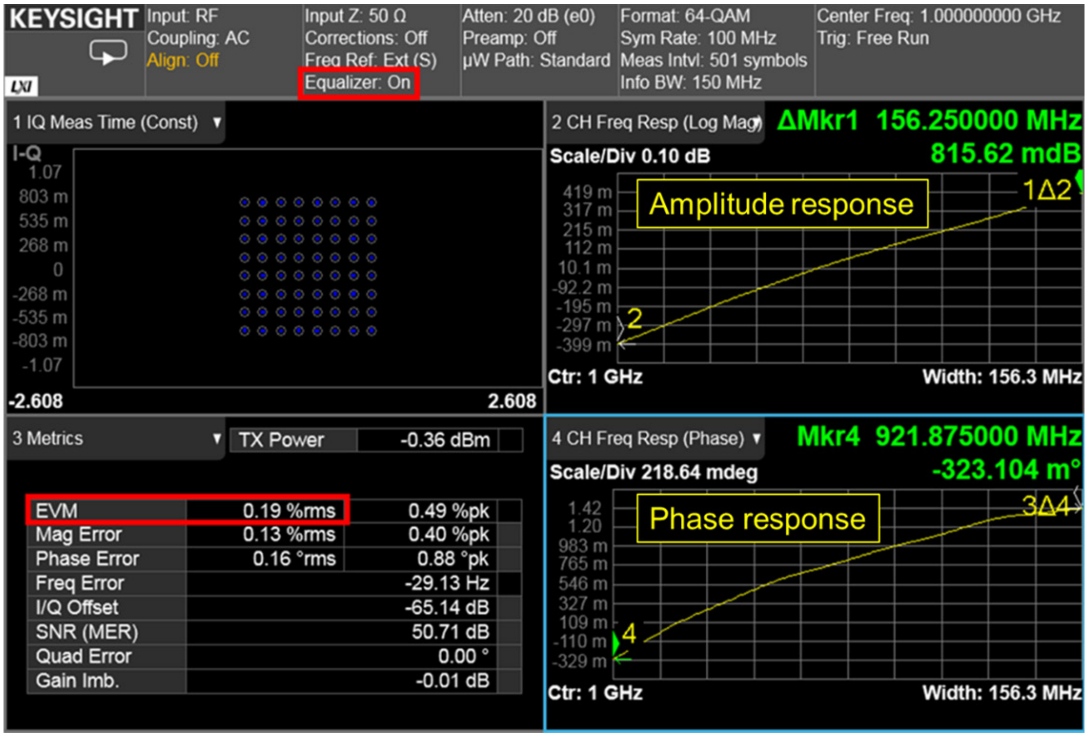

Figure 2. The signal's amplitude and phase frequency responses

Remove frequency responses with channel corrections

VSGs support an internal calibration routine that collects correction data for both the baseband and RF's magnitude and phase errors. The correction data covers the entire RF frequency range and crosses all power levels. It also includes parameters of the correction filter applied to baseband waveforms in real time.

In Figure 3, you can see the demodulation analysis of the 64 QAM signal with the internal channel correction set to on. The concentration of symbols in the upper left of the constellation diagram and resulting error vector magnitude (EVM) appear at 0.82%.

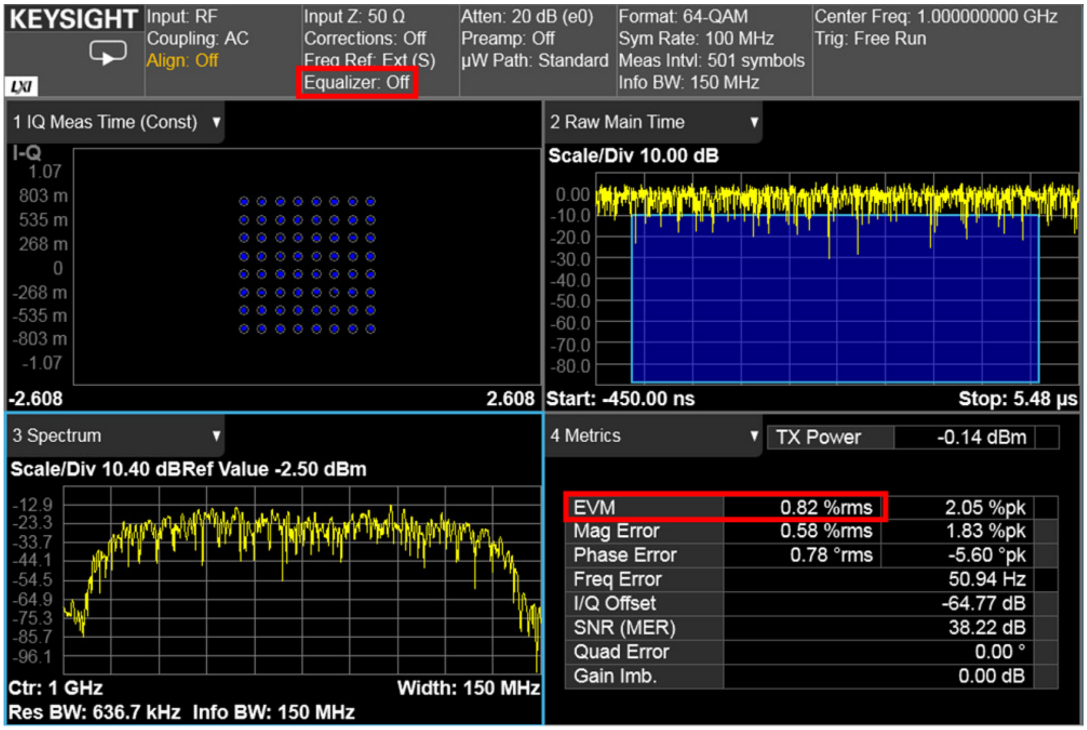

Figure 3. Signal generator with internal channel correction “on”

Extend measurement plane

Cables, components, and switches in the paths between a signal generator and a device under test (DUT) can degrade measurement accuracy because of flatness errors. You must extend the measurement accuracy from the signal generator’s output (reference plane) to the DUT’s test port, as shown in Figure 4. Any network elements (cables, connectors, or fixtures) between the signal generator and the DUT will impact the signal’s fidelity. The user channel correction calibration extends the signal generator’s performance to a new calibration plane – the user’s DUT input port.

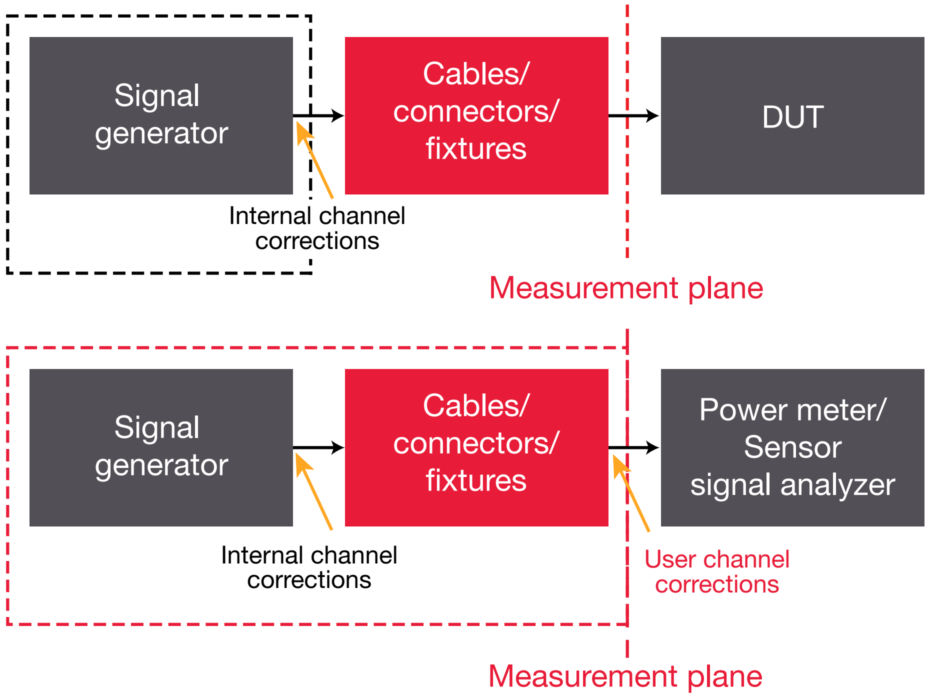

Figure 4. Move the measurement plane from the signal generator's output to the DUT's input

You can measure the responses of the network elements with a power sensor, a signal analyzer, or a vector network analyzer to obtain a corrected filter. With the Keysight VXG vector signal generator, a **measure corrections block wizard** guides you through the process of measuring and calculating corrections for an external network of cables, connectors, and other passive components between the signal generator and the DUT.

Characterizing to the network topology enables you to remove its effects from the output signal. This helps you to move the effective reference plane (the signal generator's output port) to the measurement plane. If you have multiple networks with different correction files, Keysight's VXG allows you to cascade the corrections (A and B blocks), as shown in Figure 5.

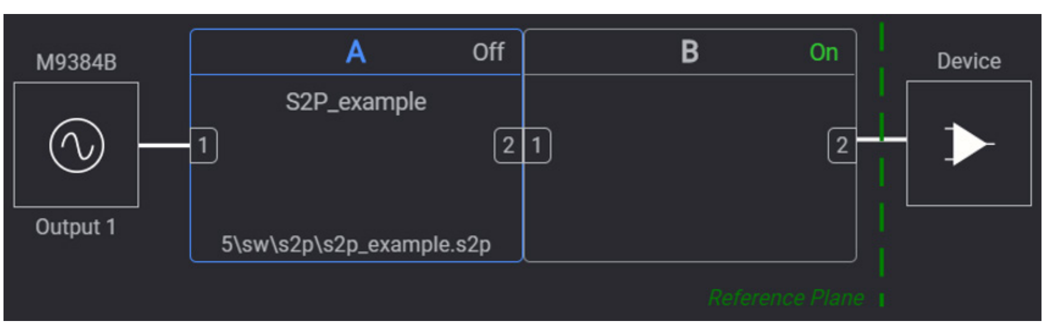

Figure 5. Cascade the channel corrections from the A and B blocks

I/Q modulator imperfections

The I (in-phase) and Q (quadrature) signals from the baseband generator's output travel to the I/Q modulator and upconvert to an intermediate frequency (IF) and RF signal. Before combining the I and Q signals, the I and Q signals mix with a same local oscillator (LO) and insert a 90-degree phase shifter in one of the LO paths, as shown in Figure 6. Each component in the I/Q modulator contributes a certain kind of error, resulting in final modulation quality.

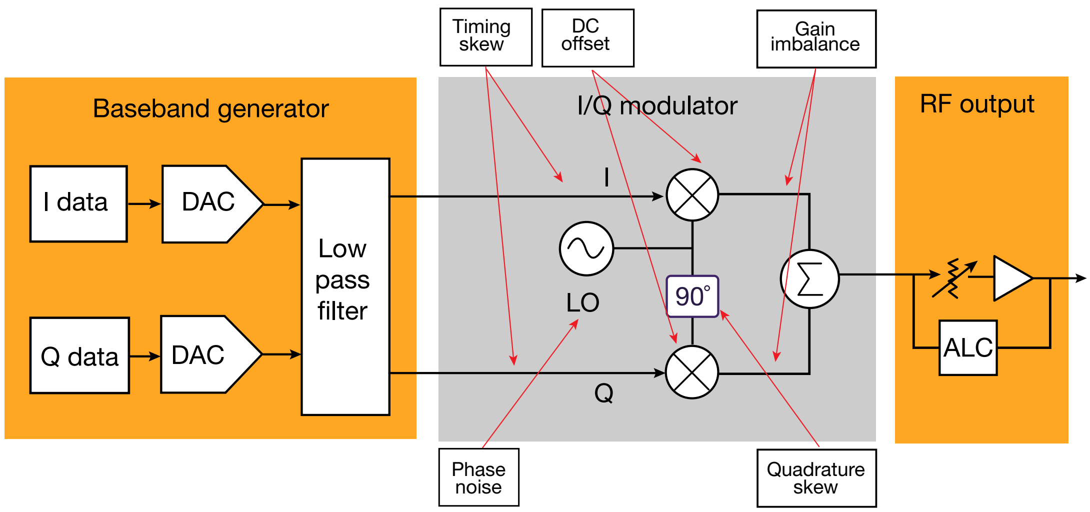

Figure 6: A block diagram of an I/Q modulator and possible errors

I/Q origin offset (carrier feedthrough)

The I/Q origin offset indicates the magnitude of RF carrier feedthrough signal or baseband DC offsets.

- **RF carrier feedthrough**: Two mixers not identically matched and balanced. This imbalance results in LO leakage that is dependent on the carrier frequency.
- **Baseband DC offset**: A DC bias injects at the I, Q, or both paths.

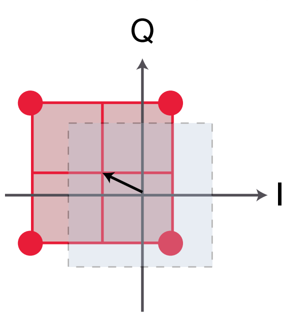

Figure 7. I/Q origin offset in a constellation diagram

I/Q mismatch errors

I/Q mismatch errors also result in unwanted images. The causes of these errors are amplitude, phase, and time differences between the I and Q signals due to baseband hardware limitations.

Amplitude mismatch (gain imbalance)

A baseband generator outputs and amplifies I and Q signals independently. The inequality gain between the I and Q paths creates an incorrect positioning for each symbol in the constellation. Figure 8 shows a QPSK I/Q signal with an I/Q gain imbalance.

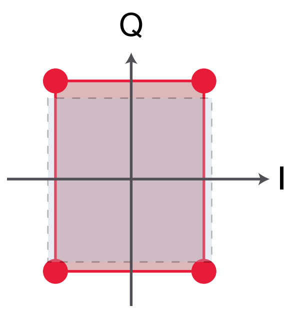

Figure 8. I/Q gain imbalance in a constellation diagram Timing mismatch (timing skew)

Timing mismatch (timing skew)

The I and Q signals travel different signal paths, creating time delay differences that appear as an error vector magnitude (EVM) error. The diagram to the far left of Figure 9 shows the QPSK I and Q signals and the constellation diagram. The I and Q signals are timing aligned, and the symbols are at corners. The diagram to the far right of Figure 9 shows that the Q signal has a timing shift. The I/Q symbols change their position, and the I and Q signals are effectively no longer in quadrature. The effects become serious when the signals have wide bandwidths (high symbol rates).

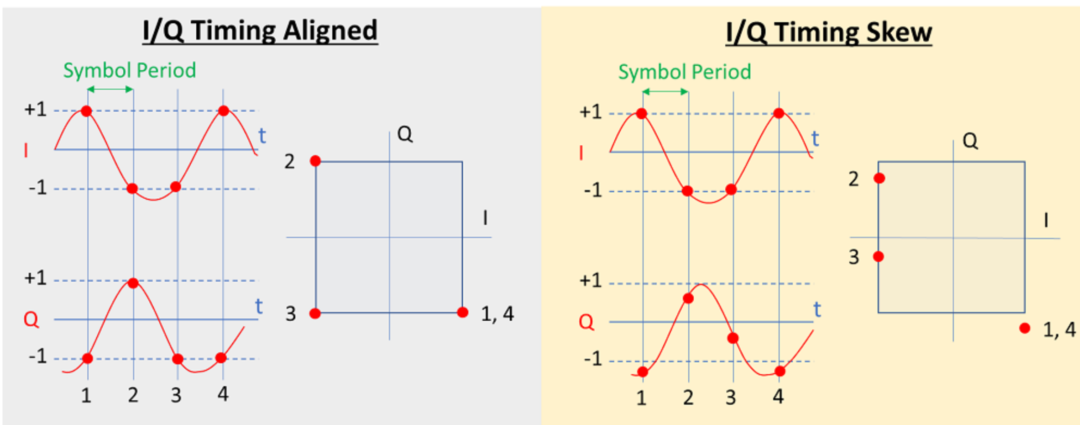

Figure 9. Example of I/Q timing skew

Phase mismatch (quadrature error)

A quadrature error occurs if the phase shift between the LO signals that mix with the I and Q baseband signals at a modulator is not 90 degrees. The error can result from a LO splitter phase error or phase matching imperfections in the mixers. Figure 10 shows a demodulated QPSK signal with a quadrature error. This result occurs when the I and Q channels are not operating orthogonally. The constellation diagram turns into a parallelogram.

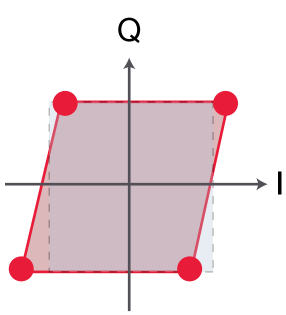

Figure 10. An impaired signal due to I/Q quadrature error

Baseband I/Q adjustments

Vector signal generators enable you to use I/Q adjustments to compensate for or add impairments to the I/Q signal. Figure 11 illustrates the I/Q adjustments setup on the Keysight VXG signal generator, including I/Q offset, gain balance, time skew, and quadrature angle. Table 5 summarizes I/Q effects and impairments available through I/Q adjustments.

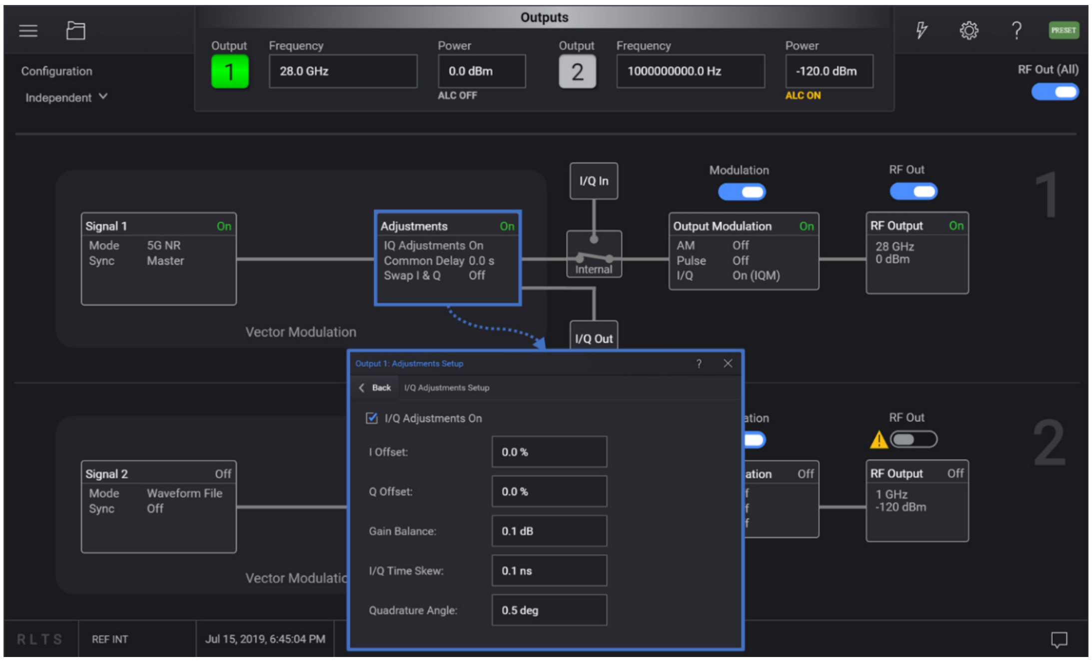

Figure 11. Baseband I/Q adjustments setup

Table 5. I/Q adjustment uses

I/Q adjustment	Effect	Impairment
Offset	Carrier feedthrough	DC offset
Quadrature angle	Error vector magnitude (EVM) error	Phase skew
	I/Q images	I/Q path delay
Time skew	EVM error	High sample rate phase skew
		I/Q path delay
Gain balance	I/Q amplitude difference	I/Q gain ratio

Direct IF/RF with DDS technology

Next-generation vector signal generators with a direct digital synthesizer (DDS) architecture can generate an IF/RF signal direct from a high-resolution, high-sampling-rate digital-to-analog converter (DAC). Figure 12 shows a traditional baseband block diagram with an analog I/Q modulator (gray block) and a direct IF/RF with DDS technology for a multitone signal generation. As you can see in Figure 12, the traditional method creates intermodulation between tones.

The lower of Figure 2 shows a direct RF/IF vector signal generator (VSG) block diagram. It implements I/Q modulator digitally and uses a high-speed DAC to directly output an RF/IF signal. The direct RF/IF with DDS technology eliminates signal impairments caused by the analog I/Q modulator. This new architecture improves signal dynamic range, especially for wideband signal generation.

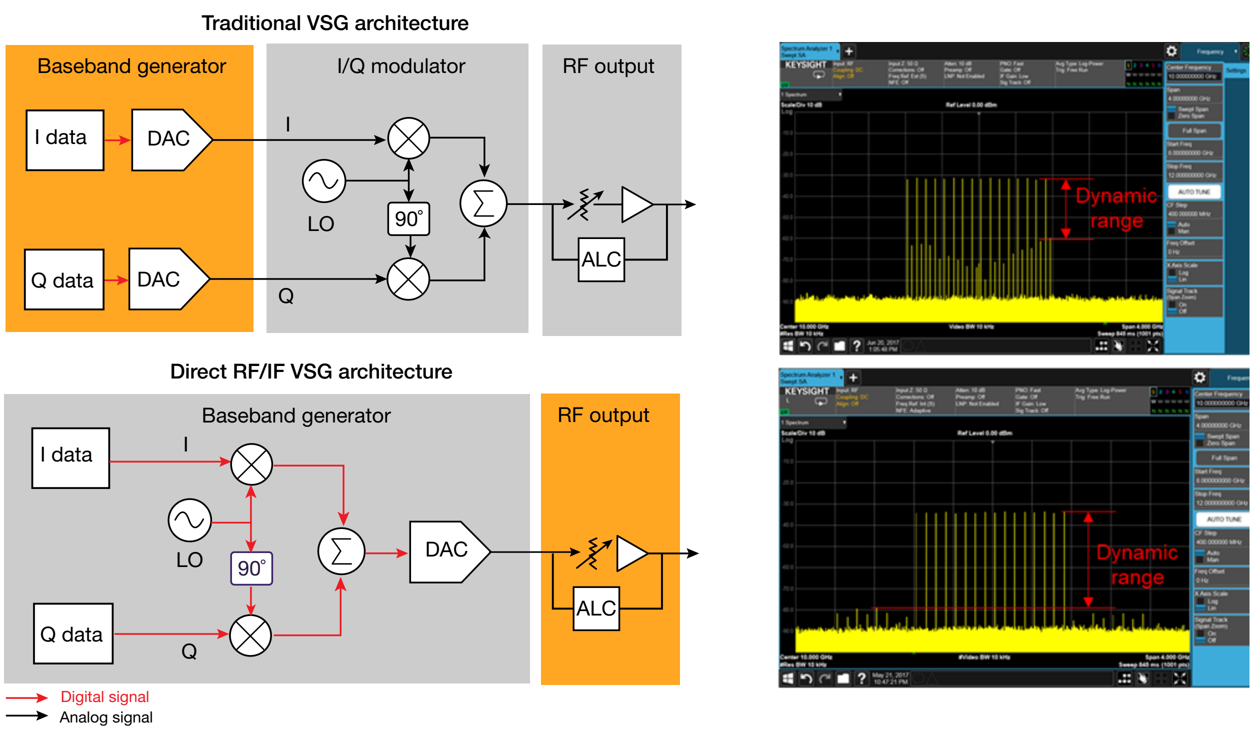

Figure 12. Comparison of analog and digital up-conversion methods

With the high dynamic range using the advanced DDS technology, the new signal generator can emulate up to 8 transmitters simultaneously per RF channel without generating intermodulation signals (images) and LO carrier feedthrough which a traditional analog I/Q modulator does. This is extremely useful for wireless receiver testing cause you need multiple signal generators to emulate wanted signals and interferers. With the DDS technology, you just need one RF channel to emulate all wanted and interfering signals as long as all the signals are within a bandwidth of 2.5 GHz. Figure 13 illustrates waveform simulation for one Wi-Fi (wanted) signal, and seven interferes including Bluetooth®, LoRa, WiSUN, LTE FDD, custom 16 QAM and a CW signal in 2.4 GHz ISM band with one RF output port. You can set up the frequency and output level in real time for each signal without the need to calibrate external accessories. The new DDS signal generators simplify the receiver test setups with better signal fidelity, simpler test setup, and cost-effective.

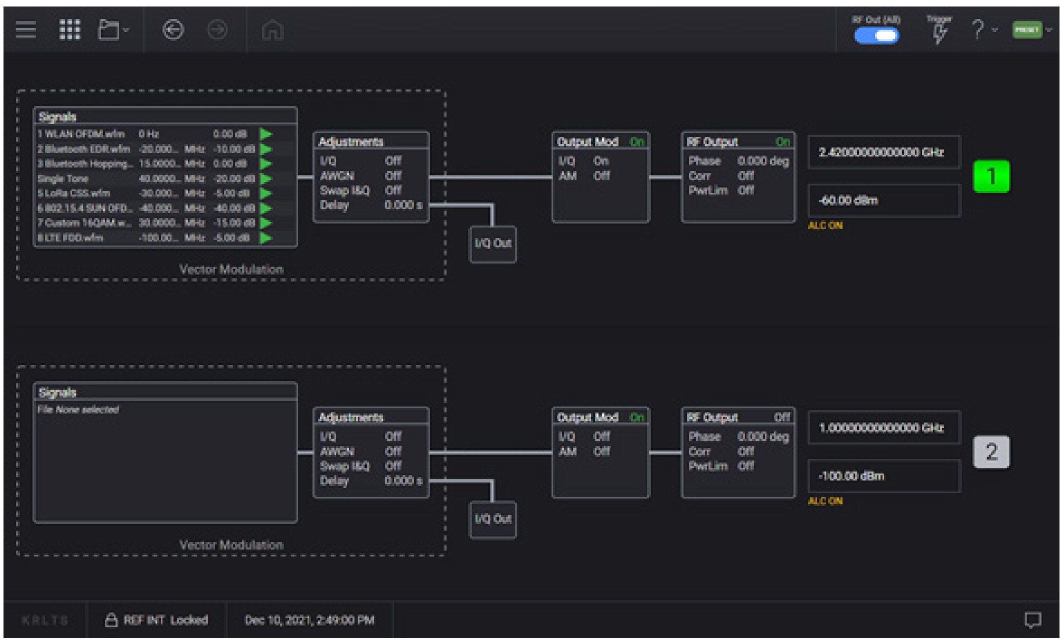

Figure 13. Setups for multiple signals with the M9484C VXG vector signal generator

Summary

As network traffic increases exponentially because of rapidly evolving wireless communications systems, it creates a strong demand for increased bandwidth to support next-generation wireless standards and technologies. You need to develop an accurate and reliable test system that delivers optimal performance to meet the requirements for wide bandwidth test applications. You learned the three common solutions to generate wide bandwidth signals and how to improve measurement integrity from this paper.

Keysight's new VXG signal generation solution enables the best signal fidelity for wide bandwidth test applications with an advanced DDS technology. The fully integrated, calibrated, and synchronized signal generation solution helps you minimize measurement uncertainty. You don't need to worry about the errors caused by additional connections and instruments.

To learn more about the VXG, please visit www.keysight.com/find/m9484C.